TEMPERATURE MEASUREMENT AND CONTROL

by Ron Tipton

For most people, the comfort zone is a fairly narrow temperature range centered more-or-less around 75 degrees F (23.9° C), which we often call "room temperature." Some of our electronic instruments are even more demanding. Crystal oscillators need a closely controlled temperature for best frequency stability. Standard cells and Zener diode voltage references also perform best in a temperature stable environment.

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In this article, we'll take a cruise through this interesting realm and look at some of the devices we use to measure and control temperature. I have summarized the most pertinent information in a Comparison Table for easy reference.

THE MECHANICAL THERMOSTAT

With the advent of electric utility companies, central heating and cooling started to appear in our living and work spaces. And we needed some means for automatically turning the heat or cooling on and off at our choice of temperature. The bimetallic strip thermostat was invented to do this job.

You can make a bimetallic strip by attaching to each other two strips of material with different expansion coefficients, such as brass and iron as shown in Figure 1. When the strip is heated, the brass lengthens more than the iron. This curls the strip away from the "cold" contact, breaking the circuit and turning off the heater. This simple mechanical device is so reliable that it's still a widely used temperature controller in homes and offices.

But this thermostat needs hysteresis (as do all on-off controllers). That is, when used for heating, the temperature at which the contacts open must be higher than the temperature at which they close. This provides a "coarser" degree of control, but keeps the contacts from rapidly opening and closing at the set-point temperature. In fact, some early thermostats (1930s) didn't have any mechanical hysteresis and had to be used with a time delay to keep the heat on long enough to get a several degree control range. Hysteresis in a typical heat cycle is shown in Figure 2.

For cooling, the temperature at which the contacts open has to be lower than the temperature at which they close. This is done by using the common and "hot" contact as shown in Figure 1.

Figure 1 — Bimetallic strip thermostat. Brass and iron are shown in this sketch, but other combinations of metals can be used.

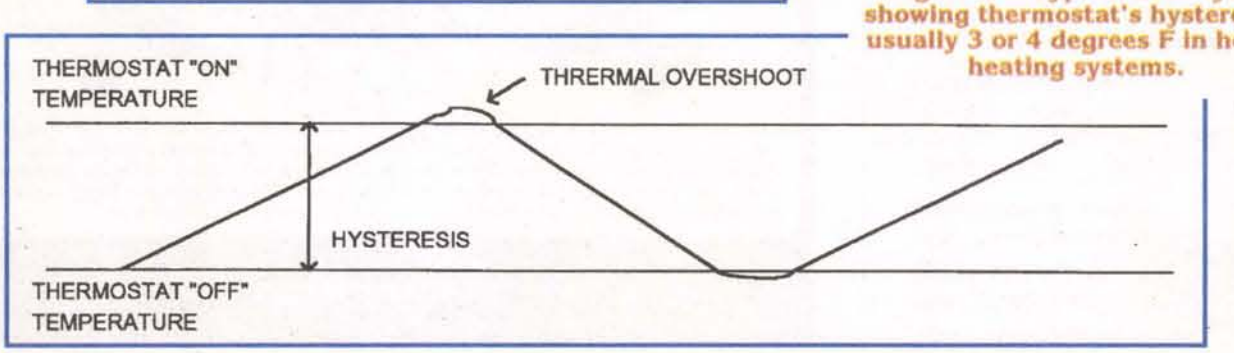

Figure 2 — Typical heat cycle showing thermostat's hysteresis, usually 3 or 4 degrees F in home heating systems.

MERCURY THERMOSTAT

Mercury has a pretty linear thermal expansion coefficient over the temperature range we're usually interested in, so mercury makes a good thermometer. Because of cost and environmental concerns, mercury has mostly been replaced by other fluids in "room" thermometers. But laboratory thermometers still use mercury although electronic units with comparable accuracy are available. Digital thermometers are easier to read, too.

Back in the 1960s, mercury column thermostats were sometimes used in lab applications. For example, they were used to control the temperature of the outer "box" in a two-stage constant temperature enclosure. Platinum wires were sealed into the glass capillary tube to make electrical contact with the mercury column. They were very reliable as long as the current was kept small, generally less than five milliamperes, so arcing never occurs.

THERMOCOUPLES

You can make a thermocouple by joining wires of different metals as illustrated in Figure 3. When the joints (or junctions) are at different temperatures, a voltage is produced which is proportional to the temperature difference.

Many kinds of wire can be used, but certain combinations have been standardized and there are tables of their output voltage vs. temperature (ANSI-MC96.1-1982). Two of the more common combinations are copper-Constantan (type T) and Chromel-Alumel (type K). Copper-Constantan has the advantage that the wires to the voltmeter can be low-resistance copper without introducing another junction between different metals.

Traditionally, the cold junction is held at 0°C in a melting ice bath and voltage-temperature tables are usually based on this assumption. But this is inconvenient (or impossible) in many applications, so the usual practice is to let the cold junction follow "room temperature" and compensate electronically for the difference above 0°C.

Thermocouples have a low output voltage (about 40 microvolts per degree C for type K) so they must be used with a stable, high input-resistance voltmeter or data acquisition system. But they are very rugged and are the only temperature sensor usable at very high temperatures — almost to the melting point of the wires. And, except for the types using an exotic metal (platinum), they are fairly inexpensive so their use continues.

THERMISTORS

Thermistors are bulk-type passive semiconductors. That is, they are made of a homogenous material, usually metal oxides.

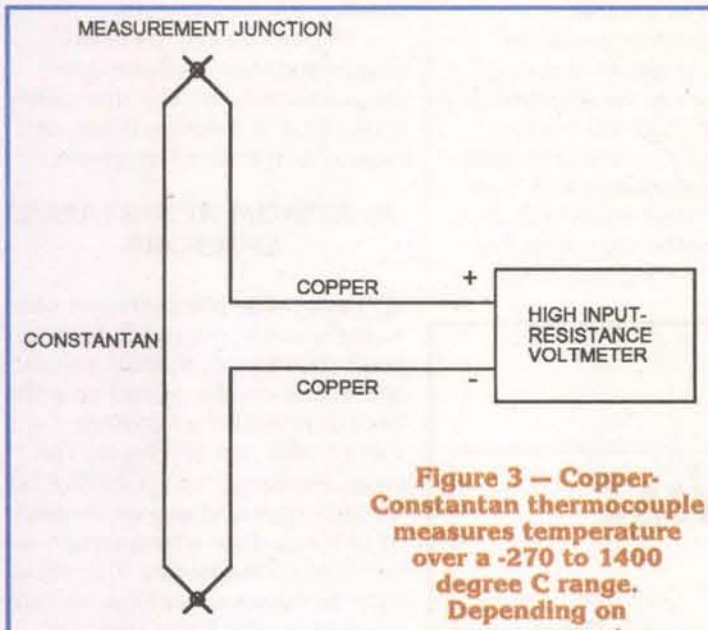

Figure 3 — Copper-Constantan thermocouple measures temperature over a -270 to 1400 degree C range. Depending on measurement temperature, junctions can be made by spot-welding, brazing, or hard-solder.

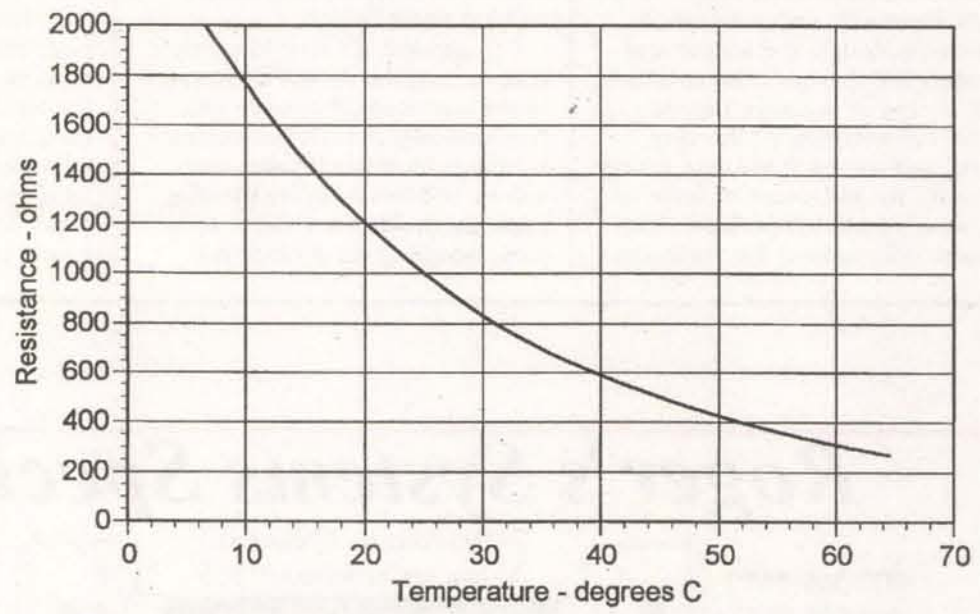

Figure 4 — Resistance-temperature curve for a typical NTC probe thermistor (Fenwal 121-102EAJ).

They exhibit a large change in resistance for a relatively small change in body temperature. Negative temperature coefficient (NTC) thermistors are usually used for temperature measurement and control because of their larger thermal coefficient as compared to their positive temperature coefficient cousins.

Because they are bulk devices, they can be fabricated in many shapes and sizes: from 0805 surface mount to large rods. Small beads and glass encapsulated probes are common in electronic applications. A typical resistance vs. temperature curve is included in Figure 4.

Thermistors have been the temperature measurement and control "work horse" for many years. They are rugged and inexpensive and about the only precaution in their use is to keep the current flow small enough to avoid self-heating. A thermometer can be as simple as an ohmmeter measuring the thermistor's resistance. Instead of ohms, the meter can be calibrated in degrees Fahrenheit or Celsius.

Thermistors are also common as the sensing component in temperature control circuits for oscillators, etc. There are as many different controller circuits as there are designers with the circuits generally falling into one of two basic types. Type 1 is direct, proportional DC control; an example circuit is shown in Figure 5. Let's look at how it works.

When the circuit is turned on, the thermistor, R6, is "cold" and the differential input voltage applied to A1 is more than three volts. A1 has a gain of 100 so its output is driven into saturation, about 6.75 volts. The voltage at pin 5 of A2 is now about 0.39 volt due to the voltage divider R8, R9. The high open-loop gain of A2 forces the inverting input voltage (pin 6) to follow the pin 5 voltage. So A2 sends enough base current into Q1 to make the voltage drop across R10 (1.2 ohms) equal about 0.39 volt. This is a Q1 collector current of about 325 milliamperes which heats Q1 and the enclosure it's attached to.

As the thermistor heats, its resistance goes down so there is less voltage drop across it. The A1 output voltage goes lower, so the A2 non-inverting (pin 5) input voltage goes lower. A2 supplies less base current to Q1 so its collector current goes down. Theoretically, the set-point is the temperature at which the voltages at pins 2 and 3 of amplifier A1 are equal. In practice, this is affected by the heat loss as set-point is approached. Good insulation is important.

R1 is a 5% resistor, but both R2 and R3 are one percenters. Also, I could see that R2 and R3 were hand-soldered to the foil side of the board. Commercial thermistors often have a 10% resistance tolerance so either you have to use a trimmer pot or hand-pick a resistor or two to get the desired set-point temperature.

In the second circuit type, the thermistor's resistance change varies an oscillator's pulse width. This duty-cycle change produces a corresponding change in the average heater power. You may argue that this approach is less sensitive to DC drift than direct DC control. This is probably true, but well-designed circuits of both types perform well in commercial use.

In either type, the heating element can be one or more power transistors thermally connected to the enclosure to be controlled. The sensing thermistor can be epoxied or otherwise attached (mechanically and thermally) to the enclosure near the heater. An example of this construction is shown in the Figure 6 photo.

Sometimes the thermistor is merely placed on the controller PC board along with the other components. Then the board is placed inside the controlled enclosure. In this case, the thermistor is sensing the air temperature instead of the enclosure temperature. Although there may be a thermal gradient in the enclosure's air space, a stable temperature at the thermistor should indicate a stable temperature at the crystal or other critical

RESOURCES

ANSI-MC96.1-1982, Thermocouple temperature/EMF tables
American National Standards Institute
1430 Broadway, New York, NY 10018
(Portions of the tables are also reprinted in temperature sensor catalogs.)

Analog Devices, Inc.
1 Technology Way
Norwood, MA 02062-9106; 800-262-5643 or on-line at www.analog.com

Circuit Cellar INK Magazine
4 Park Street, Suite 20, Vernon, CT 06066
860-875-2199 or on-line at www.circuitcellar.com

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www.elmwoodsensors.com

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www.fenwall.com

YSI, Inc.
P.O. Box 279, Yellow Springs, OH 45387
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Platinum resistance sensors
Minco Products, Inc.
7300 Commerce Lane
Minneapolis, MN 55432-3177
612-571-3121 or www.minco.com

National Semiconductor
2900 Semiconductor Drive
Santa Clara, CA 95052-8090
800-272-9959 or www.national.com

Omega Bond thermally conductive epoxy
Omega Engineering
1 Omega Drive, Stamford, CT 06907
800-826-6342 or www.omega.com

component. However, there can be a problem with using still air to thermally couple the sensor and heater. The thermal time constant will be 10s of seconds, perhaps even 100 seconds. At the very least, this means it will take a long time for the enclosure to settle to its steady-state temperature. The heater will overheat the enclosure because the sensor response is lagging so far behind.

In general, it's best to tightly couple both the sensor and heater to the enclosure, thermally and mechanically. A metal enclosure conducts heat much faster than still air and has a higher thermal capacity (holds more heat) so close coupling will provide the best temperature control.

Flexible resistance heating pads are also available in a range of sizes. These can be attached to the inside or outside surfaces of the enclosure. Of course, the heated region is surrounded with insulation, usually rigid foam or fiberglass. This lessens the amount of heater power needed and helps stabilize the temperature.

As you can see, there are many variations on thermistor-sensed enclosures. But this clearly shows that one design is not necessarily better than the others.

PLATINUM RESISTANCE SENSORS

Small gauge platinum wire can be wound on a rod to form a small diameter cylindrical sensor or the wire can be wound on a flat form to resemble a "postage stamp" with two wire leads. The Minco Products, Inc., S32PB11 is the later type and can be cemented to the surface whose temperature is to be measured. The sensitivity or resistance change vs. temperature is very linear over the whole useful measurement range, as shown in Figure 7.

Platinum sensors are very accurate and stable and they are also rather expensive. But when you need precise measurement or control, this sensor is by far the best choice. Thin-film platinum sensors are available for applications with relaxed requirements at much lower cost. For example, the Minco Products S245PD12 has a resistance tolerance of ±0.12% at zero degrees C at a small quantity price of only $4.00. The thin-film repeatability and long-term stability are almost as good as those of their higher-priced relatives.

The National Institute of Science and Technology (NIST) used a platinum sensor to control the temperature of the inner enclosure for their standard cell groups. The temperature instability over periods of several days is less than 0.00002°C (20 microdegrees). Figure 8 shows a block diagram of this controller. So how does this circuit work?

The 400 Hz oscillator is a Wein bridge circuit with an amplitude drift of less than 0.005% so as to have negligible effect on the controlled temperature. The oscillator output drives a two-stage transformer with an electrostatic shield between the stages. A tapped auxiliary transformer provides the temperature adjustment by effectively varying the turns ratio between the two transformer stages. The transformer output is coupled to a 400 Hz bandpass filter through a platinum sensor, which is the temperature controller.

The bandpass filter reduces 60 Hz noise. The 400 Hz amplifier "block" is actually two opamps in cascade which provide 90 dB gain. This output goes to a phase-sensitive detector used as a rectifier. The DC amplifier provides the current gain to drive the heater.

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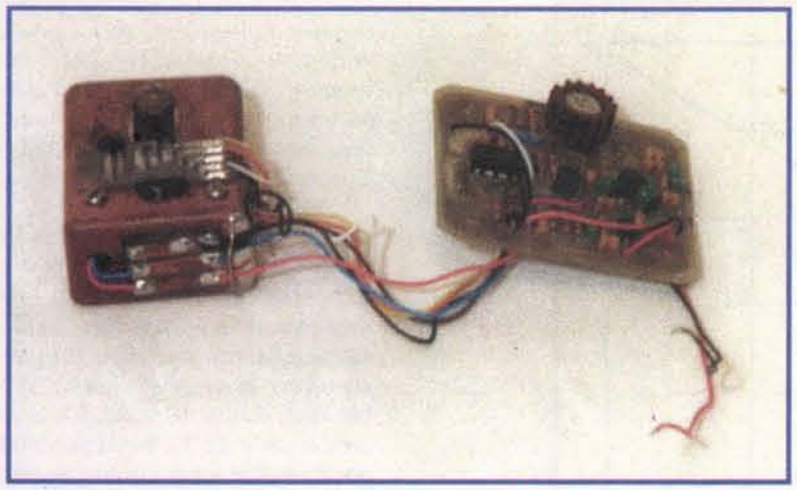

Figure 6 — Frequency control crystal oven showing the power transistor used as the heater and the temperature sensing thermistor.

Having most of the system gain at 400 Hz gives better overall stability than is possible with DC control.

ACTIVE SOLID-STATE SENSORS

Over the last several years, many active solid-state temperature sensors have been introduced. Some have digital outputs while others are analog. The Dallas Semiconductor DS1620 is an example of the digital type and lends itself to building a digital-display thermometer (for an example, see the article in *Circuit Cellar INK* for June '95, page 72).

ANALOG DEVICES TMP01

This sensor has a temperature-proportional output voltage and two user programmable temperature trip points. You can easily set an over and under-temperature logic output with three external resistors. These outputs will provide the hysteresis for an electronic thermostat, or sound an alarm, or open a relay. Of course, you also have the analog output for measurement or control.

This IC operates from a single supply voltage, 4.5 to 13 volts, and comes in an eight-pin DIP, SOIC surface mount, or TO-99 metal can. The metal can is especially easy to use because the chip die is thermally attached to the can. The DIP and SOIC aren't as convenient because the epoxy package is a rather good thermal insulator. Heat is primarily conducted to the die by the metal leads. So, if you are wanting to use this sensor to control an enclosure's temperature, how do you attach it?

You need good thermal contact to the usually metal enclosure, but you also need electrical insulation. One approach is to solder the wire leads to the needed pins (three pins for temperature control) and then embed the sensor in a "glob" of thermally-conductive epoxy (such as Omega Bond OB-101) on the enclosure. This holds true for other eight-pin epoxy packages that need to be in good thermal contact with a surface.

The TMP01 can be used between -55 and +125°C with a typical accuracy of ±0.5°C over this range. Its analog output voltage (VPTAT) is five millivolts per (degree) Kelvin which equals 5 mV x (degrees C + 273), or about 1.49 volts at +25°C. Five millivolts per degree is a good signal level for short distances to the measurement or control circuit, but as the distance increases, resistance loss in the wire and noise pickup can degrade accuracy. Figure 9 shows a simple way to preserve low-error performance with a voltage-to-frequency converter. At the other end, the original analog voltage can be recovered with a frequency-to-voltage converter.

Analog Devices has a data sheet and design program for Microsoft Windows which will give you the details on choosing the external programming resistors. Free on request.

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SILRX — $26.00 ea.
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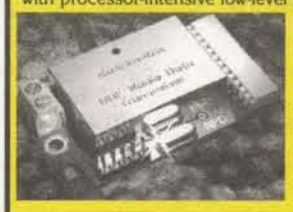

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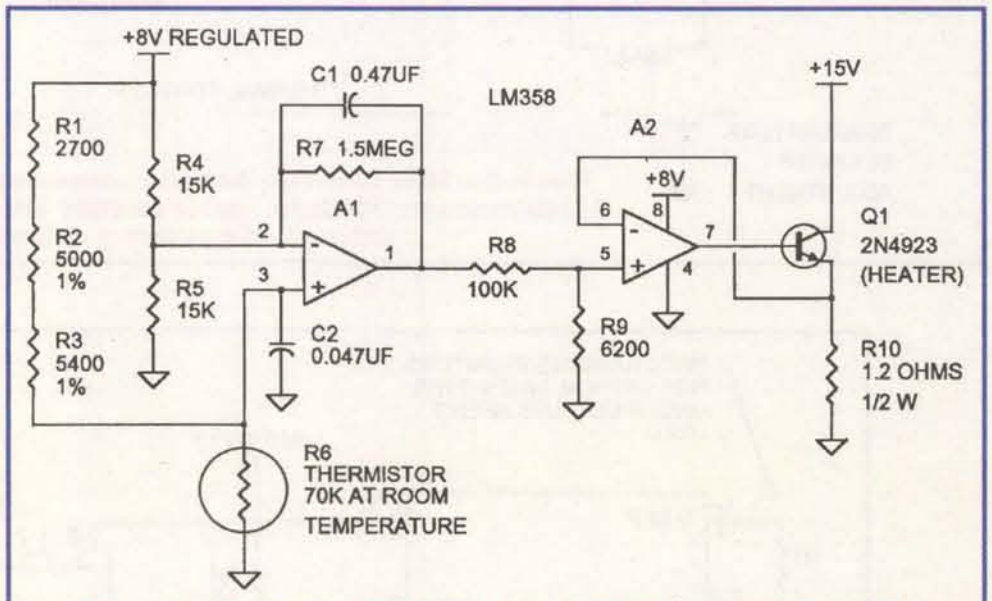


Figure 5 — Crystal oscillator heater circuit using proportional DC control. Thermistor is in thermal contact with the heated enclosure.

ANALOG DEVICES TMP03

This three-terminal sensor has a serial digital output which consists of a squarewave with a variable duty cycle. This is illustrated in Figure 10. You can use a counter or microprocessor to measure the T2 time interval which is proportional to the temperature. A single-wire interface is about as simple as it gets!

This sensor will operate from 4.5 to 7 volts and supply current is just 1.3 milliamperes maximum at five volts. The TMP03 comes in three epoxy packages: a TO-92, an eight-pin SOIC, and TSSOP surface mount. In the eight-pin units, five pins are unused.

The TMP03 has an accuracy of ±4°C maximum over its -25 to +100°C operating range so it's basically less accurate than the TMP01. However, its simple digital interface may compensate for its lower accuracy. This article isn't meant to be a comprehensive survey of ALL active temperature sensors. For any measurement or control problem, get data sheets on every one you can find and compare the specs.

NATIONAL SEMICONDUCTOR LM34, LM35, and LM45

These are all three-terminal sensors with an analog output voltage proportional to tempera-

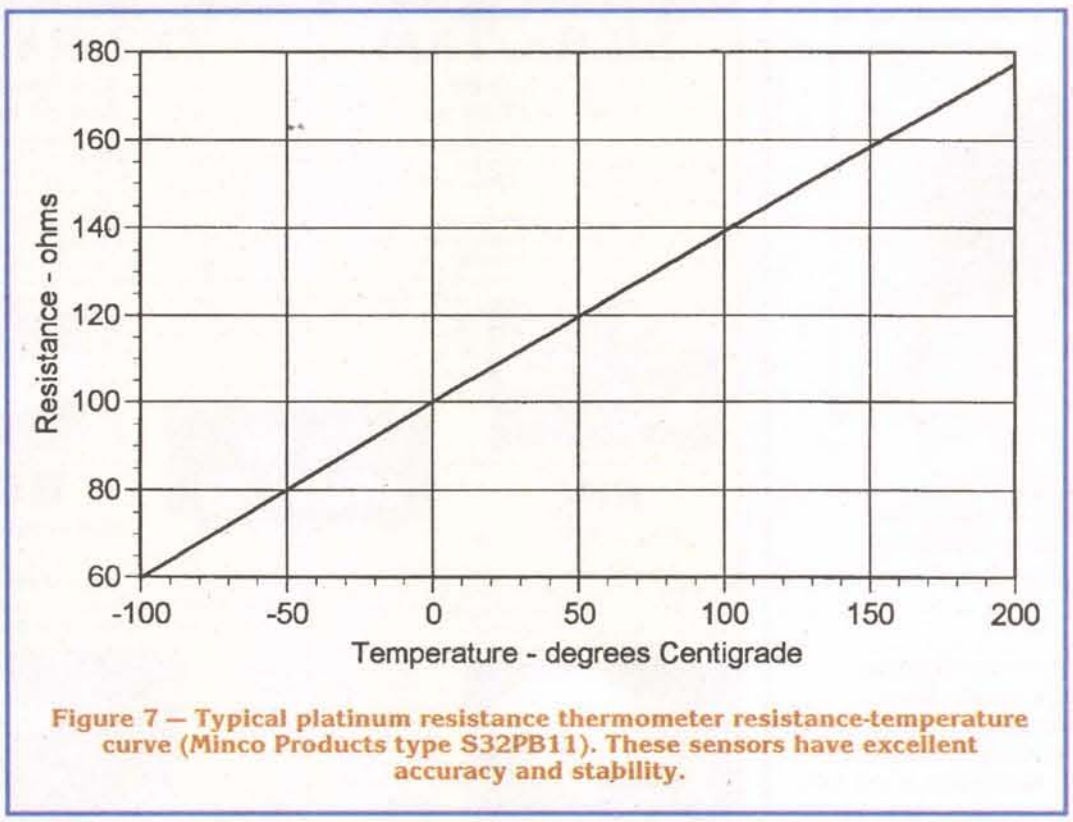


Figure 7 — Typical platinum resistance thermometer resistance-temperature curve (Minco Products type S32PB11). These sensors have excellent accuracy and stability.

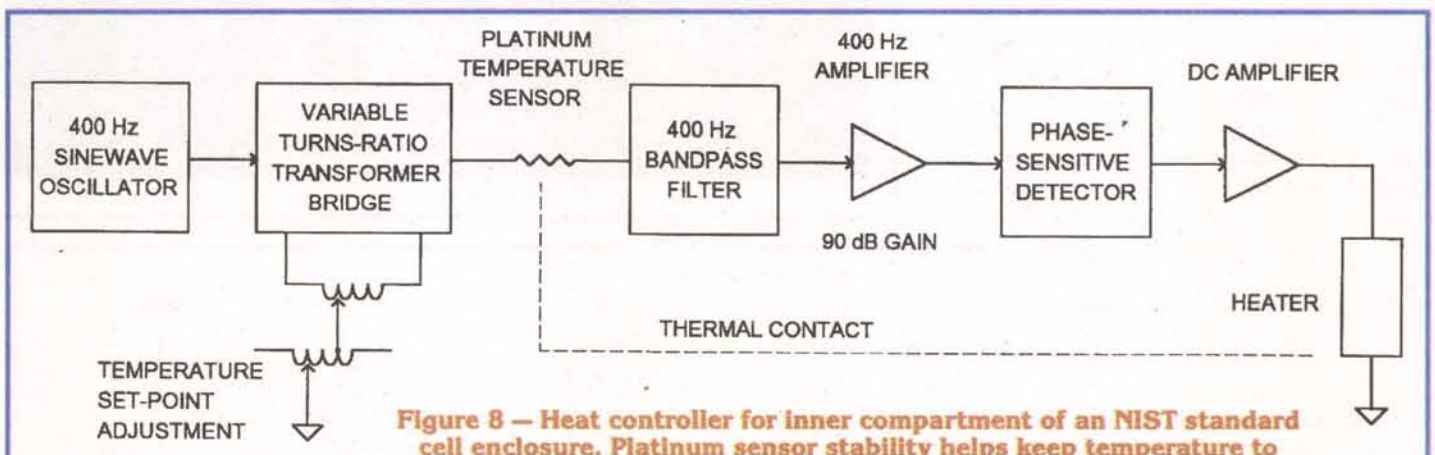


Figure 8 — Heat controller for inner compartment of an NIST standard cell enclosure. Platinum sensor stability helps keep temperature to within 20 microdegrees of the set-point.

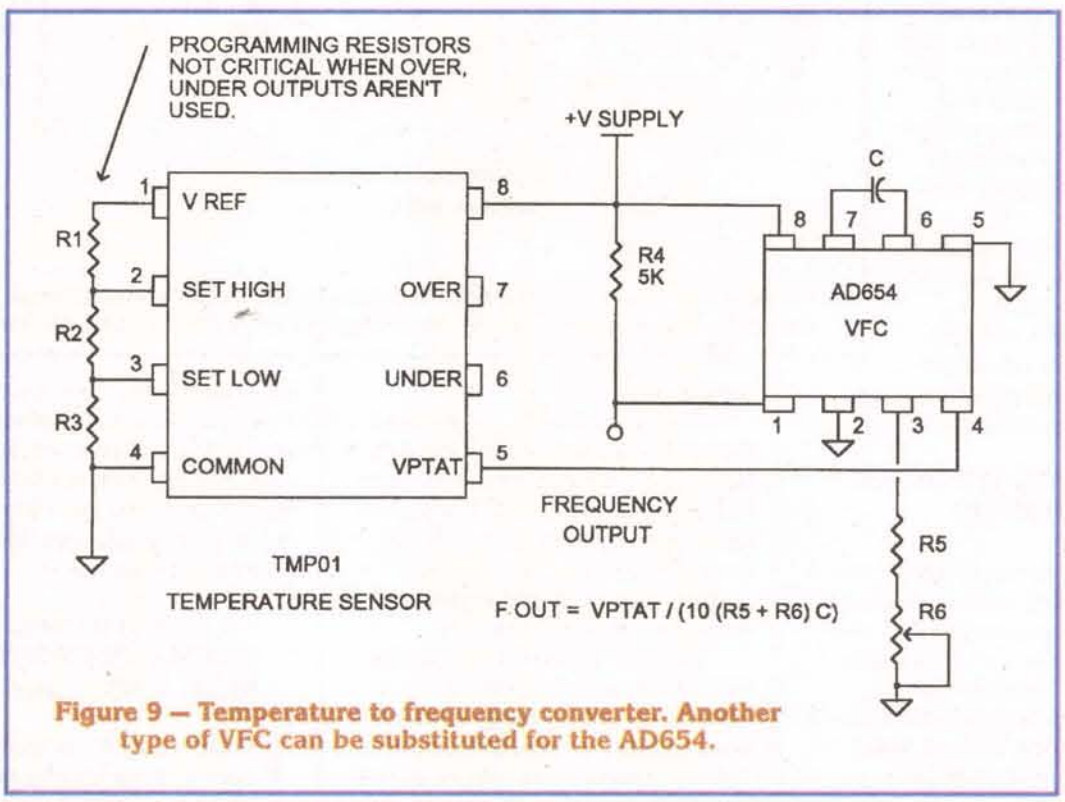


Figure 9 — Temperature to frequency converter. Another type of VFC can be substituted for the AD654.

ture. The LM34 is calibrated in degrees Fahrenheit, and the LM35 in degrees Celsius. Both of these come in TO-46, TO-92, and surface mount SO-8 packages and they can be ordered from Digi-Key Corporation (see Resources list).

The LM45 is calibrated in degrees Celsius, has an output of 10 millivolts per degree over a temperature range of -20 to +100, and comes in a teeny-tiny SOT-23 surface mount package. It operates from a supply voltage between 4 and 10 volts. It's accuracy is only ±3°C, but it seemed a good choice for a control application since stability is often more important than the actual temperature. The 10 mV per degree is a good, hefty signal to work with. Besides, I had a couple of free samples.

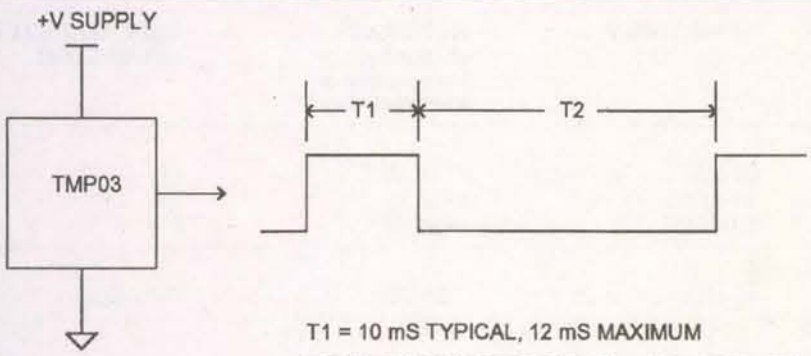
Earlier I mentioned that another type of controller used a variable pulse duty cycle to control the average heater power. I needed this type controller in a particular application because the circuit becomes battery operated during power outages. On-off control of the amplifier that supplies the heater current is very efficient. This circuit is diagrammed in Figure 11. Let's take a look at how it works.

IC1 is connected as a low frequency oscillator (about 3 Hz) with a sawtooth output taken from pin 2. Q1 and its associated resistors (R1, R2, and R3) supply a constant current which makes the sawtooth ramp-up more linear than just using a single resistor. The sawtooth is applied to the non-inverting IC3 input.

The amplified sensor voltage goes to the inverting input. IC3's output goes high whenever the sawtooth voltage equals or exceeds the sensor voltage at the inverting input. The result is a pulse whose width is proportional to the sensor temperature.

When the circuit is first turned on, the sensor is at room temperature and the sawtooth voltage is always higher than the sensor voltage. IC3's output stays high and maximum heater current flows through Q2. As the sensor heats, its output voltage goes up and the circuit goes into pulse mode. The dissipation in Q2 is very low because it is either on or off, and the power MOSFET has a very low on resistance.

The heater, shown as the flat rectangle in the Figure 12 photo, is a flexible stick-on unit with a resistance of about 55 ohms so maximum heater power is a low four watts. Heat up time is a very


+V SUPPLY
TMP03
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T2
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TEMPERATURE (DEGREES C) = 235 - ((400 x T1) / T2)
IF T1 AND T2 ARE MEASURED WITH THE SAME CLOCK, SMALL DRIFTS ARE CANCELLED BY THE MATHMATICAL DIVISION.

Figure 10 — Analog Devices TMP03 temperature sensor serial output timing.

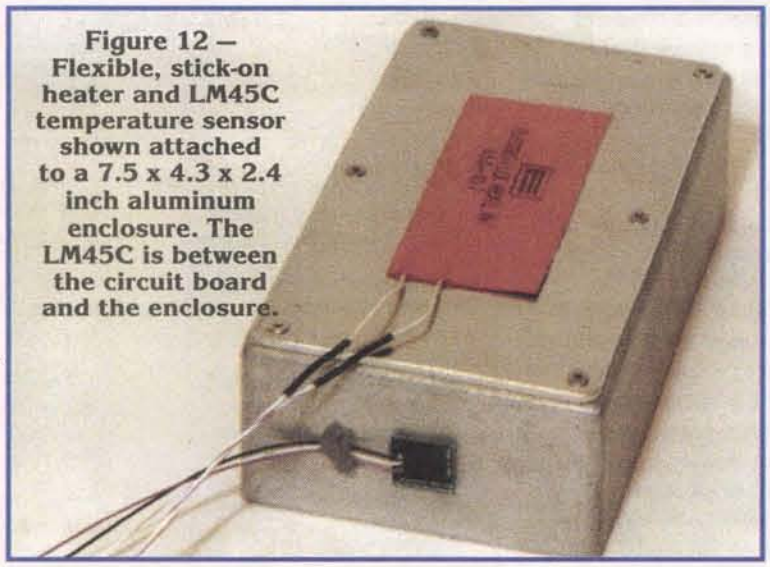

Figure 12 — Flexible, stick-on heater and LM45C temperature sensor shown attached to a 7.5 x 4.3 x 2.4 inch aluminum enclosure. The LM45C is between the circuit board and the enclosure.

long several hours, but this circuit is intended to be on all the time so low power consumption seemed more important. The power decreases to about 1.2 watts at the set-point temperature in a box with three inches of rigid foam insulation on all sides. Temperature stability after warm up is a "straight line" at my measurement resolution of 0.05°C.

The LM45C is soldered to a small PC board along with its three wire leads. Then I stuck it to one end of the aluminum enclosure, sensor towards the enclosure, with a bit of Bondo Plastic Metal (see photo). This stuff seems to work, as well as thermally conductive epoxy and it's available at your corner hardware store.

Set-point temperature is determined by the gain of amplifier IC2 and it's set by varying the resistance of R4, as shown in Figure 13.

Constant temperature control systems that are left on all the time should have an over temperature monitor. This can be as complex as using an LM75, which we'll be looking at next, or as simple as a mechanical thermostat which opens at a temperature 5 to 10 degrees higher than the set-point. A variety of thermostats can be found in the Elmwood Sensors catalog. Ask for a copy.

NATIONAL SEMICONDUCTOR LM75

The LM75 is a temperature monitor, analog-to-digital converter, and digital over-temperature detector with a serial interface, all in a tiny eight-pin SO-8 surface mount package.

This sensor has a three line address input, so up to eight units can share an address bus. The host computer or microprocessor can program the over-temperature set-point and read out the temperature at any time over the serial interface. The temperature data

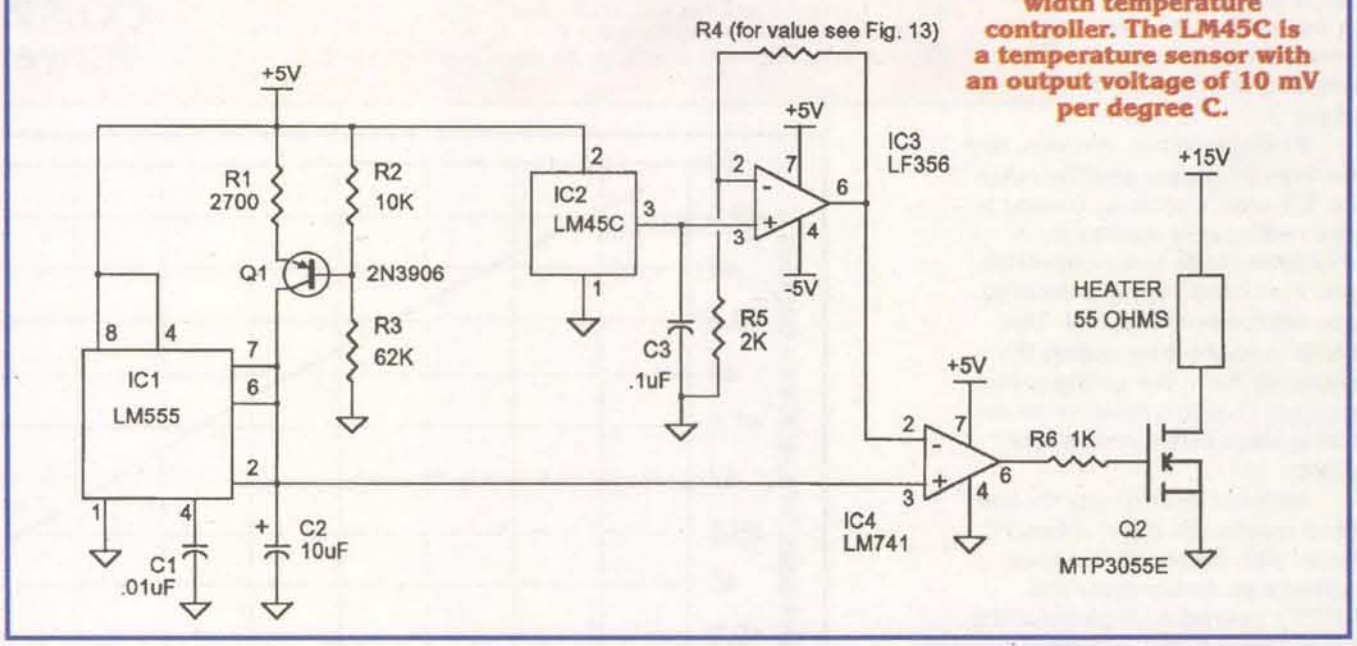

Figure 11 — Variable pulse width temperature controller. The LM45C is a temperature sensor with an output voltage of 10 mV per degree C.

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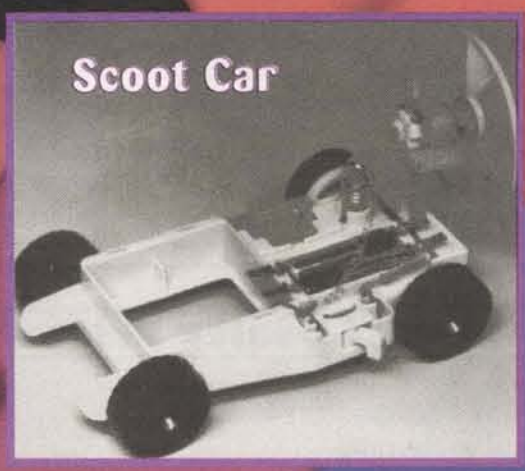

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format is a nine-bit, two's complement word with the least significant bit equal to 0.5°C.

The LM75 can be used as an over temperature protector by programming a host microprocessor to monitor the temperature and then sound an alarm — play "Dixie," light a lamp, or just open a relay to disconnect heater power if the limit is exceeded. Default over-temperature is set to 80°C on power-up, so this sensor can be used as a stand-alone thermostat at this setting. An independent over-temperature output is provided at pin 3.

Available in two versions, one for five-volt supply and the other for 3.3 volts, operating current is one milliampere maximum. A shutdown mode is also available which reduces supply current to one microampere typical. This mode is enabled by setting the shutdown bit in the configuration register. Over-temperature monitoring stays active during shutdown.

National Semiconductor had (and maybe still does) a free PC board with Microsoft Windows software to demonstrate the LM75's operation. A photo of the LM75 demo board and smaller LM60 demo board is shown in Figure 14.

Many active, solid-state sensors aren't even touched on here, but this is a representative sample. Collect all the data sheets and catalogs you can find and compare specs. Then the next time you have a temperature measurement or control problem, the information in this article will help get you pointed in the right direction. **NV**

COMPARISON TABLE
TEMPERATURE SENSORS

SENSOR TYPE	USEFUL TEMPERATURE RANGE	SENSITIVITY	ACCURACY (Actually, inaccuracy or uncertainty)	REPEATABILITY (STABILITY)
Thermocouples				
Chromel-Constantan (type E)	-270 to 400°C	60 uV/°C	±1 to ±5°C	[1]
Chromel-Alumel (type K)	-270 to 1400°C	40 uV/°C	±1 to ±5°C	[1]
Copper-Constantan (type T)	-270 to 1400°C	40 uV/°C	±1 to ±5°C	[1]
Thermistors				
Fenwal 121-102EAJ (glass bead)	-100 to 300°C	40 ohms/°C at 25°C	0.25°C[2]	0.25°C[3]
Platinum Resistors				
Minco S245PD (thin film)	-70 to 400°C	0.4 ohm/°C	0.3°C	0.1°C
Minco S32PB	-62 to 220°C	0.4 ohm/°C	0.1°C	0.1°C
Reference thermometer	-180 to 500°C	0.4 ohm/°C	±0.025°C	0.0025°C/year
Active Solid-State Sensors				
AD TMP01	-55 to 125°C	5 mV/°C	±1.5°C max	0.25°C typical
AD TMP03	-25 to 100°C	0.12 mS/°C	±4°C max	0.5°C typical
NS LM45C	-20 to 100°C	10 mV/°C	±3°C max	0.12°C typical
NS LM75	-25 to 100°C	0.5°C[4]	±2°C max	0.5°C typical

Notes: [1] depends on environment
[2] 1% tolerance probe or with calibration
[3] if used at less than 100 degrees C
[4] 9-bit word with least significant bit equal to 0.5 degree C

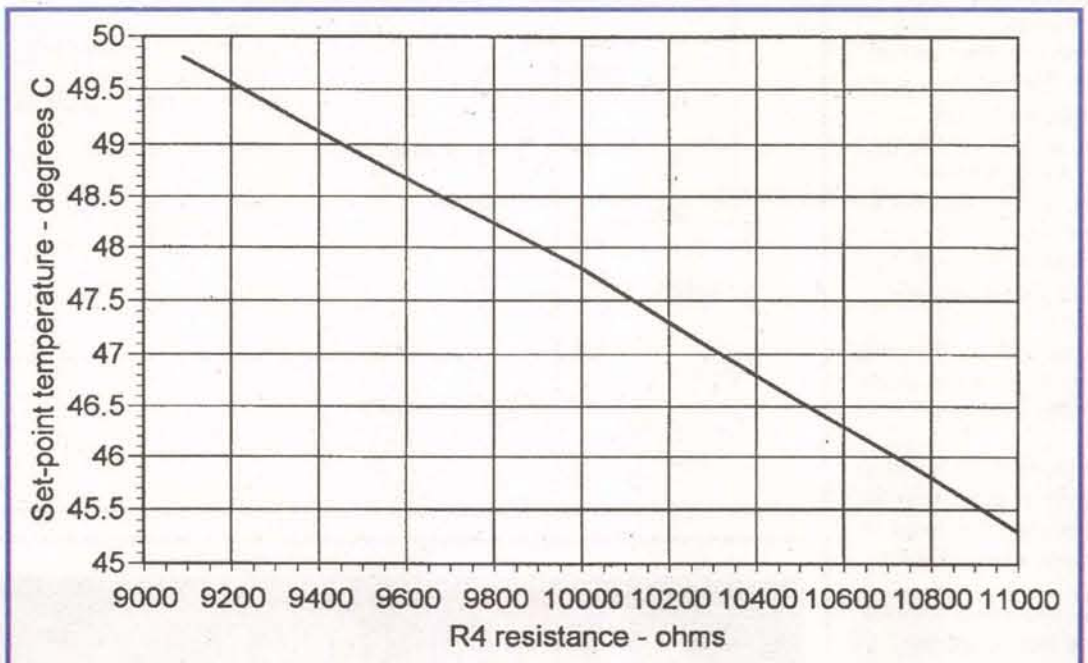

Figure 13 — Set-point temperature control in the variable duty-cycle controller using an LM45C temperature sensor.

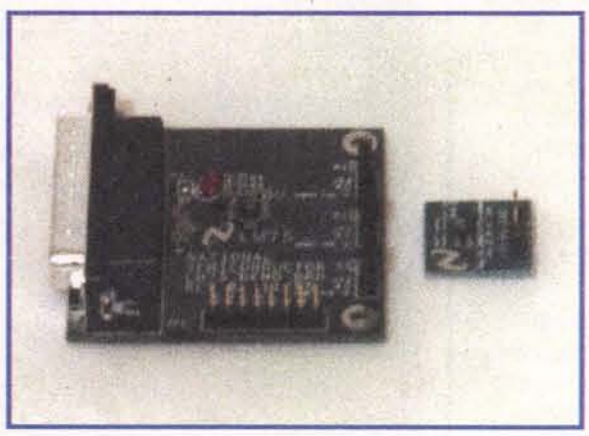

Figure 14 — National Semiconductor LM75 and LM60 (smaller) temperature sensor demo PC boards. The LM75 board has an RS-232 port for connection to a Microsoft Windows computer. Demo software is supplied with the board.

I've also collected some useful TM&C info (including the Circuit Cellar INK thermometer article) on our Web site as a "zipped" PDF (Adobe Acrobat) file. Go to www.zianet.com/tdl and click on Magazine Article Reprints. Find this article and then click tm&c.zip to download. If you don't have the free Adobe Acrobat Reader, there's a link on our home page to download a copy.

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